SIMULTANEOUS DETERMINATION OF ORIENTATION AND THICKNESS IN ANISOTROPIC MEDIA

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INTRODUCTION

Ultrasonic travel-time techniques are commonly utilized for thickness determination in parts where the properties of the material are well characterized. Typically, this use has been limited to isotropic materials (where the ultrasonic velocity used to determine the thickness is independent of the direction of propagation in the material). For anisotropic materials, the situation is considerably more complicated due to the directional dependence of the ultrasonic velocity. If the orientation of the material is known, then the same approach used for isotropic samples can be used for thickness determination, providing one properly accounts for the known anisotropy in velocity. When the orientation and thickness are both unknown, a new approach must be utilized to avoid errors arising from the intrinsic variation in the ultrasonic velocity due to anisotropy.

BACKGROUND

While there is considerable research in the use of ultrasonic techniques to characterize texture in polycrystalline metals (1-5), relatively little work has been done on the problem of orientation determination in single crystal materials. There is one study, which explores the possibility of using an ultrasonic approach to orient single crystals when the material properties are known. Green and Henneke (6) describe a graphical technique which requires the measurement of two independent elastic wave speeds (longitudinal or shear modes).

Green and Henneke's approach was based on the observation that every distinct crystal orientation is associated with a unique combination of longitudinal and shear wave velocities. This can be readily seen if one plots contours of constant velocity for the three modes of bulk wave propagation for the standard stereographic triangle such as the aluminum single crystal shown in Figure 1. If one overlays any two of these plots one can see that each combination of the two orientation angles needed to completely specify crystal orientation is located at the intersection of one contour from each of the velocity plots. Conversely, if one measures the velocity of acoustic wave propagation for each mode and locates the intersection point of their

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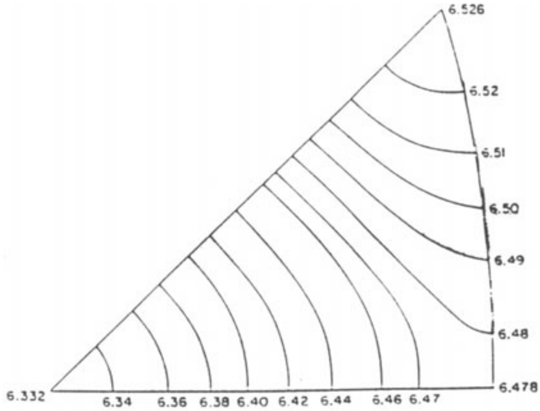
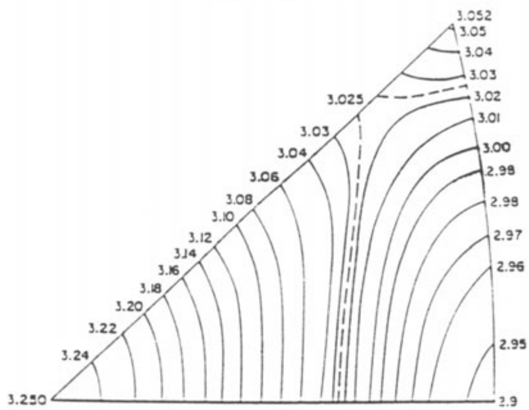
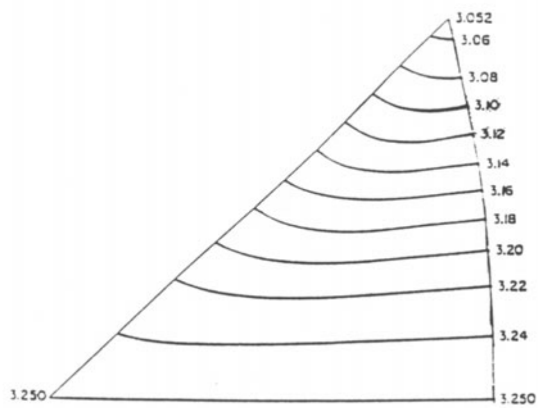


a) Longitudinal



b) Fast Shear



c) Slow Shear

Figure 1 Velocity contours (Al single crystal, after Green & Henneke (6)).

associated contours, the corresponding crystal orientation is determined. The third plot can be used as a check on the measurement. Since it is a graphical technique, there is an inherent uncertainty associated with manually locating the contour intersection points. This places stringent limits on the precision needed to orient a typical crystal. Green and Henneke (6) estimate that the acoustic velocities must be measured to within 0.1% for this approach to be useful.

A more common approach to single crystal orientation utilizes x-ray diffraction to achieve this end. This technique is accurate and nondestructive, but measures only the material properties at the surface and the sample size is exceedingly small. This makes x-ray diffraction impractical unless one is willing to cut a small portion from the sample for testing. In this case, the approach is no longer nondestructive.

RECONSTRUCTION ALGORITHM

The approach is based on the observation that the velocity of ultrasonic wave propagation is a function of the elastic properties of a material, its direction of propagation and the density. Knowing the anisotropy of the material, one can readily predict the velocity of wave propagation in any given direction. Conversely, by measuring the variation in velocity with direction, one can characterize the anisotropy. This is a key factor in reducing the uncertainty in thickness measurements in anisotropic media via ultrasonic travel time methods.

This approach requires that the symmetry class and unit cell mechanical properties be known. A minimum of three independent measurements are needed to extract the three unknowns (two orientation angles and the thickness) from the ultrasonic data. These data may be acquired point by point in direct contact (using longitudinal and shear transducers to generate the required wave modes). In addition, more than three measurements can be used in the inversion to improve the accuracy of the results.

The data analysis algorithm is based on the ability to accurately model acoustic wave propagation in an anisotropic material for any orientation. This analysis is based on the basic governing equation (Christoffel equation)

$$C_{ijkl} l_j l_l - \rho v^2 \delta_{ik} = 0 \qquad (1)$$

where

C_{ijkl} = Elements of Stiffness Tensor
ρ = Density
l_j = Components of Wave Normal
v = Phase Velocity
δ_{ij} = Kroneker Delta

This is a 3 x 3 eigenvalue equation for any wave propagation direction l in the material where the eigenvalues yield the acoustic velocities. Hence, in any direction, there are three possible acoustic velocities corresponding to three possible polarizations of the particle displacement (one longitudinal and two shear). The direction of propagation is specified by two orientation angles θ and ϕ) relative to the crystallographic axes where

$$l = \begin{matrix} l_1 \\ l_2 \\ l_3 \end{matrix} = \begin{matrix} \sin\phi\cos\theta \\ \sin\phi\sin\theta \\ \cos\phi \end{matrix} \qquad (2)$$

Therefore, the three possible acoustic velocities can be determined for any orientation of the single crystal. The variation in these velocities in space is often depicted by a velocity surface where the radius represents the velocity in that particular direction. With this approach, the

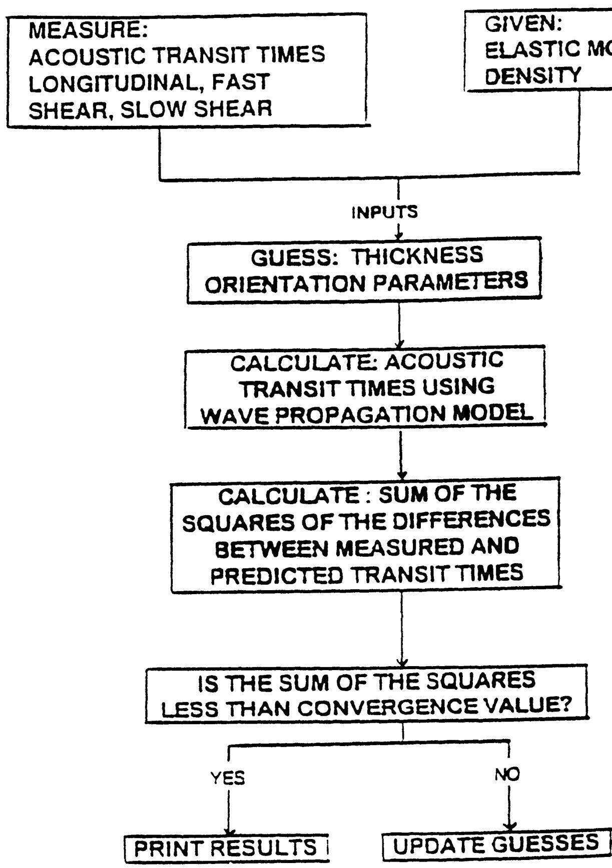


Figure 2. Data Processing Flow Chart .

velocity surface for each mode in an isotropic media is a sphere since the velocities are the same in all directions. With an anisotropic material, the surfaces are distorted from being spherical. The greater the deviation from spherical, the greater the anisotropy. The method is suitable for any anisotropic material of known symmetry, providing the elastic properties of the have been determined. A flow chart for the data processing is shown in Figure 2.

In practice, since we measure transit times and not velocities, the program is designed to compute the transit times for each mode of propagation as a function of thickness and the two crystal orientation angles. The reconstruction algorithm is an iterative search to find the best match between predicted and measured acoustic transit times for each of the three modes of propagation (one longitudinal and two shear). To run the program one first inputs the measured transit times along with an initial guess for the part thickness and orientation. The program then determines the predicted transit times for each mode and compares them to the measured data. Next, the least squares minimization routine is invoked to find the next guess for thickness and orientation angles. This is done using a commercial (IMSL) subroutine, which uses a Levenberg - Marquardt approach with a numerical Jacobian to update the guesses. The acoustic transit times for these new guesses are then compared with the measured values. If the sum of the squares of the differences between the predicted and measured transit times fall below a predetermined threshold level, the algorithm has successfully converged to yield the part thickness and orientation. Otherwise, the process is repeated until convergence is achieved. The method is relatively insensitive to the initial guess (one can be in error of +/- 40% of the actual values in the initial guess values and still get successful convergence).

EXPERIMENTAL SYSTEM

A schematic diagram of the data acquisition/analysis system is shown in Figure 3. Here,

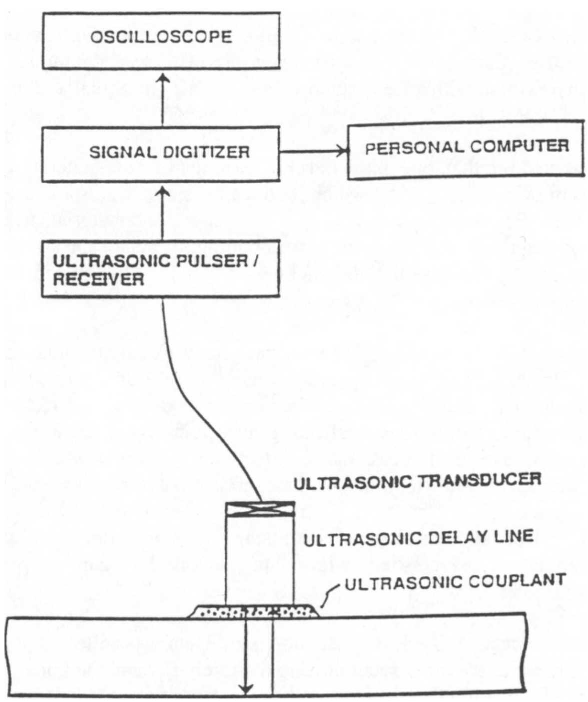


Figure 3. Data Acquisition System.

Table 1

Parameter	Actual	Reconstructed (ave)	Std. Deviation
thickness	1.0000 mm	1.00004	0.00330
ϕ	1.30899 rad	1.30923	0.00896
θ	0.54409 rad	0.55009	0.00362

both longitudinal and shear piezoelectric transducers are directly coupled to the part under investigation. A coupling fluid is used to provide an efficient means of transmission of ultrasonic energy into the part. The transducers serve both as transmitters and receivers of ultrasound. A pulser-receiver is used to provide the initial electrical stimulation to the transducer (which launches the wave into the part) as well as amplifying the received ultrasonic signal information for processing. Three time of flight measurements are generally made- one longitudinal and two transverse (with orthogonal polarization)..The polarization of the shear transducers is adjusted by rotating the element to yield the maximum and minimum in signal transit times. This information is then input into the computer for data processing to determine the part thickness and orientation.

RESULTS AND DISCUSSION

To test the utility of this approach, a series of 3000 tests were run with synthetic data to simulate experimental error. Each of the transit time measurements was assumed to be distributed in a Gaussian fashion with a 2.5% standard deviation. The actual and reconstructed values are as shown in Table 1.

It should be pointed out that, due to the intrinsic symmetry of the material, there might be multiple combinations of orientation angles, which produce the same results and are totally equivalent to one another. For cubic crystals (the case for many of the materials used currently), for example, there are 24 equivalent orientations corresponding to each of the stereographic triangles. However, symmetry provides that the thickness determined by this method would be correct regardless of which stereographic triangle is selected.

Once the validity of the approach was proven for synthetic data, the next step was to apply it to a real part. One of the first concerns in this regard was the ability to accurately and automatically determine transit times from the acquired acoustic waveforms. This was of particular concern due to the lack of a perfect reflecting surface in several locations. Two algorithms were developed based on 1) Peak Signal Detection , 2) Autocorrelation. A reproducibility study was conducted with multiple, independent measurements made at the same site in a typical part. Figure 4 shows these results and the improvements (with respect to simple peak detection) resulting from additional signal processing. With autocorrelation, we can reproduce our measurements at a given site to within 0.027%. Similar figures were obtained for the two orientation angles.

The next step was a test of a typical production part. Data was collected at a variety of sites around the circumference, the outer section being relatively flat and the inner section being curved. The ultrasonically measured part thicknesses were then compared with results from a ball micrometer. This comparison was found to be quite good as demonstrated in Figure 5. A small offset in the two data sets is noted,

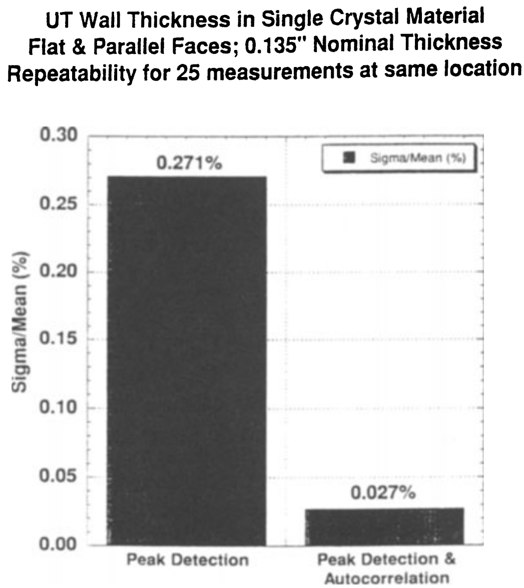


Figure 4. Reproducibility study results

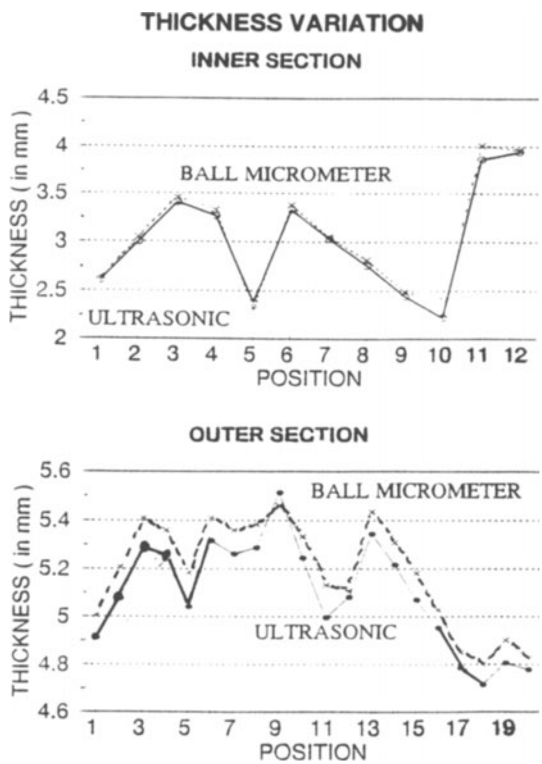


Figure 5. Test results

possibly due to small variations in composition from part to part and the associated small changes in material properties resulting from this variation. This measurement difference was found to be well within the allowable limits for thickness determination for the part. As a result of this development effort, a production test system was developed and is currently in use to insure the dimensional integrity of every manufactured part.

CONCLUSIONS

A method and supporting algorithms and devices are described for measuring the unknown thickness of a part fabricated from a material with a known anisotropic velocity distribution but where the orientation of the material is initially unknown. The approach requires initial knowledge of the symmetry class and material properties of the base material. Three transit time measurements are utilized and a computer algorithm is used to determine the local thickness and crystal orientation at the measurement site. Results were shown indicating good agreement between the nondestructively determined part thicknesses and direct ball micrometer measurements.

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